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Modeling and Simulation of Self Excited Induction Machine for Wind Power Generation

R. Janakiraman [1] and S. Paramasivam [2]
[1] Sri Ramanujar Engineering College, Anna University/Electrical and Electronics Engineering, Chennai, India
Email: janakiraman67@yahoo.co.in
[2] R&D Head, ESAB Engineering Services Ltd., Irungattukottai, India. Email: paramsathya@yahoo.com

***Abstract*—Objective of this paper is to propose modeling and simulation of self-excited induction machine for wind power generation (SEIMWPG). The earlier models of such generators capable of generating electric power are facing huge mechanical losses due to wear and tear in the tightly coupled mechanical gear systems. Due to this heavy arrangement in each and every constituent mechanical assembly, the earlier design could not provide maximum efficiency. In this paper the proposed model focuses on the performance of the system using the concept of variation of mutual inductance in the generator windings. This new model can be possible to generate maximum power with the variation of mutual inductance of stator and rotor windings irrespective of the variation of wind velocities. The complete system is modeled and simulated in the MAT LAB/ SIMULINK environment. The results of this renewable model and design are to promote green energy systems in the future.**

***Index Terms*—Self-excited induction generator (SEIG), mutual inductance, wind power generator (WPG), doubly-fed induction generator (DFIG).**

I. Introduction

Wind energy research has developed significantly over the past few years. In spite of this development, more technological advances are needed to make wind energy competitive with many other energy supply techniques. The variation of the mutual inductance of stator and rotor windings of SEIG has taken care of the wind speed fluctuations and to maintain the output voltage generation at rated value has been presented in [1]. In [2], the modeling and simulation can be used to study the performance calculations of wind power generating systems. In this model of SEIG, variation of the magnetizing inductance is the main factor in the dynamics of voltage build-up and stabilization which have been also given. In a DFIG model, the effects of several parameters are (drive-train inertias, stiffness, generator mutual inductance, and stator resistance) operating points (rotor speed, reactive power loading, and terminal voltage level), and grid strength (external line reactance value) on the system modes which have been studied in [3]. A complete analysis of a WT driven SEIG as a part of a supply system to an isolated load has been carried out. To achieve this, a new simplified model has first been derived for a WT driven SEIG system [4]. A detailed DFIG based wind turbine model, including two-mass drive train, pitch control, induction generator, back-to-back PWM converters, and vector-control loops have been developed [5].

The development is based on applying a mixture of linear and nonlinear control design techniques on three time scales, including feedback linearization, pole placement, and gradient-based minimization of potential function which has been studied [6]. A new algorithm has also been presented in order to minimize the torque and flux ripples and to improve the performance of the basic direct torque control (DTC) scheme [7]. A real-time model of a DFIG-based grid-connected WTGS model has been developed with accurate and efficient manner through the real-time simulator [8]. The calculation of all the machine inductance as by the inductance matrices is formulated, and it is the key to the successful simulation of an induction machine which has been presented in [9]. In [10], a new hybrid high voltage direct current (HVDC) connection for large wind farms with DFIGs system model which has also been described and derived.

In [11], the d-q-modeling for the three phase self-excited induction generator (SEIG) with squirrel cage rotor and its operating performance have been evaluated. The steady state performance of the SEIG with different optimization technique is available and the effects of various system parameters have been presented in [12], [13] and [17]. In [14], artificial intelligent techniques are used to model the control strategy for proper reactive compensation under different operating conditions and to maintain the terminal and load voltage. A series-parallel compensation system tracks the maximum power curve of the wind turbine and this system can be scaled up to a higher voltage and higher power to process very high power in SEIG based wind power generation which has been studied [15].

A number of approximations and simplifications had to be made to describe the fault behavior and to determine the equations for the short circuit current analysis of DFIG has been studied [16]. The new control strategies to tackle problems such as vibration and ride through and the mechanical phenomena of DFIG based wind turbine have been presented in [18]. The coordinated voltage control scheme of SEIG based Wind Park is to improve the network voltage profile and for minimizing the steady-state loading of the STATCOM it effectively supports the system during contingencies which has been presented in [19]. A permanent magnet stator-less contra-rotation wind power generator (PMSLCRWPG) test model is designed and tested for various wind speeds and voltages. This model will be suitable for the large scale and better solution for future energy crises [20].

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II. Proposed Model of Self-Excited Induction Machine for Wind Power Generation

It is proposed that a wind turbine is coupled with a Self-Excited Induction Machine (SEIM) for electric power generation. In this case, no mechanical gearing system has been utilized; because of mechanical losses like wear and tear and mechanical friction losses, the mechanical gearing replaced by an electrical system, as discussed in Fig.1, which shows the flow diagram of the wind power generating system. Where, v_w is the wind speed in metres/second, L_m is the mutual inductance of the windings in henries, V_G is the voltage generated and V_k is the rated voltage output. The first step is to initialize the process of operation; the second step is to propose the variables involved in the process, such as wind speed, mutual inductance of the stator and rotor windings of the SEIG and voltage generation.

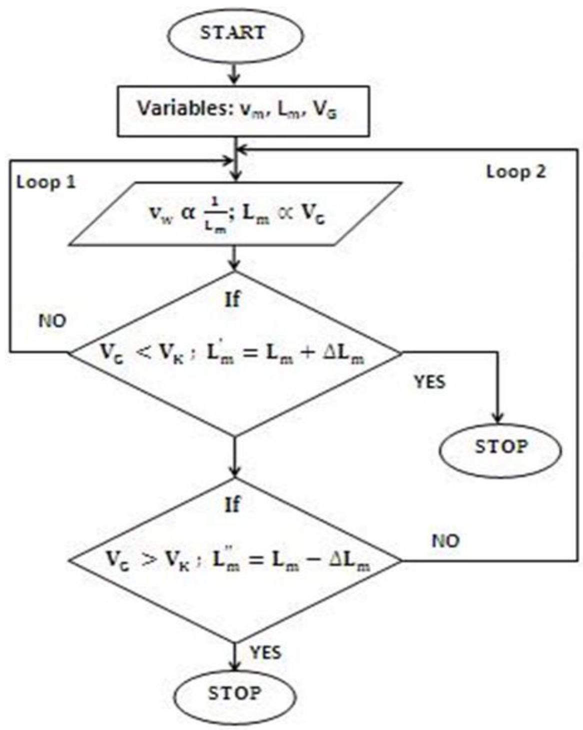

Figure 1. Flow diagram of the proposed SEIMWPG

The main variable is the mutual inductance of the SEIG, in which it is dependent on the speed of the wind turbine, based on the wind velocity. The third step is the variation of the mutual inductance, in which it is inversely proportional to the wind velocity, and voltage generation which is directly proportional to the mutual inductance of the windings of the SEIG. The fourth step is, if the voltage generation is less than the rated value, the loop.1, is directed to increase the mutual inductance of the SEIG and to increase the voltage generation up to the rated value. The fifth step is, if the voltage generation is more than the rated value, loop.2, is directed to reduce the mutual inductance of the SEIG and, to reduce the voltage generation up to the rated value. Thus, the wind power generation is always maintained rated value, irrespective of the variation of wind velocities.

III. Model of SEIMWPG

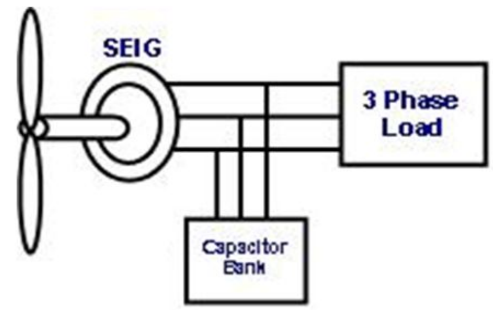

Figure 2(a). Schematic Model of SEIMWPG

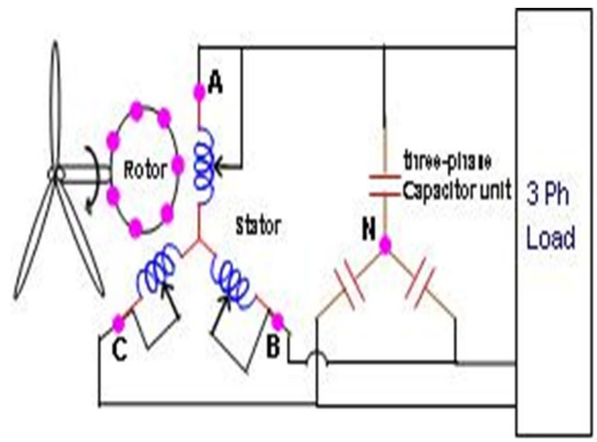

Figure 2(b). Circuit Model of SEIMWPG

A three phase induction machine has been converted as a self-excited induction generator with a three-phase capacitor bank of a sufficient value is connected across the stator terminals. When the rotor of three phase induction machine is externally driven at a suitable speed and it can generate electricity. Fig.2 (a), shows the schematic diagram of a SEIMWPG system. Whenever, the induction machine is driven at the required speed, the residual magnetic flux in the rotor will induce a small e.m.f. in the stator winding. The suitable capacitor bank causes this induced voltage to continue to increase until an equilibrium state is attained, which is due to magnetic saturation of the machine. Fig.2 (b), shows the circuit model of SEIMWPG, in which it has been designed as the mutual inductance of the winding is made as variable with respect to the variation of rotor speed. It can be varied as, if the rotor speed is above the normal speed, the mutual inductance is made to reduce and if the rotor speed is below the normal speed, the mutual inductance is made to increase; these arrangements are required to maintain the generation output and to meet the rated voltages.

IV. Mathematical Model of a Self-excited Induction Machine

The equation shown is used for developing the dynamic model of the SEIM,

$$[V_G]= [R_G][i_G]+[L_G]p[i_G]+\omega_{rG}[G_G][i_G] \qquad (1)$$

Where, $[V_G]$ and $[i_G]$ represents 4x1 column matrices of voltage and which is given as

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$[V_G]=[V_{sd}\ V_{sq}\ V_{rd}\ V_{rq}]^T$ and $[I_G]=[i_{sd}\ i_{sq}\ i_{rd}\ i_{rq}]^T$, [R], [L] and [G] represents 4×4 Matrices of resistance, generator inductance and conductance as given. The L_m is the magnetizing inductance, which can be obtained from the analysis.

$$[L]=\begin{bmatrix} L_{sd} & L_{dq} & L_{md} & L_{dq} \\ L_{dq} & L_{sq} & L_{dq} & L_{md} \\ L_{md} & L_{dq} & L_{rd} & L_{dq} \\ L_{dq} & L_{mq} & L_{dq} & L_{rq} \end{bmatrix};$$

$$[G]=\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & L_m & 0 & L_r \\ -L_m & 0 & -L_r & 0 \end{bmatrix};$$

$$[L]=\begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \quad (2)$$

The relation between L_m and i_m is given as

$$L_m=\frac{|\psi_m|}{|i_m|} \quad (3)$$

Where $|\psi_m|$ and i_m are the magnetizing flux linkage and magnetizing current respectively. The equation defining L_m $V_s|i_m|$ used in the model is,

$$|i_m|=1.447 * L_m^6 - 8.534 * L_m^5 + 18.174 * L_m^4 - 17.443 * L_m^3 - 7.322 * L_m^2 - 1.329 * L_m + 0.6979 \quad (4)$$

L_{dq} used in matrix L represent the cross saturation coupling between all axes in space quadrature and is due to saturation.

$$L_{dq}=L_m+\frac{i_{md}}{i_{mq}}*L_{dq} \quad (5)$$

$$L_{mq}=L_m+\frac{i_{mq}}{i_{mq}}*L_{dq} \quad (6)$$

It follows that the above equations representing, L_{dq}, L_{md} and L_{mq} that under linear magnetic conditions, $L_{dq}=0$ and $L_{md}=L_{mq}=L_m$, as expected. The two axes values of the total stator and rotor inductances are $L_{sd}=L_{sl}+L_{md}$, $L_{sq}=L_{sl}+L_{mq}$ and $L_{rd}=L_{rl}+L_{md}$, $L_{rq}=L_{rl}+L_{mq}$. The above equations L_{sl} and L_{r1} are the leakage inductances of the stator and rotor, respectively. Because of saturation, L_{sd} and L_{sq}, but it follows from previous arguments that under linear magnetic conditions, $L_{sd}=L_{sq}$. Hence $L_r=L_{rl}+L_m$. The electromagnetic torque developed by the generator is given by

$$T_e=\left(\frac{3}{4}\right)*p*L_m*\left(i_{sq}i_{rd}-i_{sd}i_{rd}\right) \quad (7)$$

Thus, it is seen that Eq. (1) consists of four first order equations. An induction motor is hence represented by these four first order differential equations. Because of the non-linear nature of the magnetic circuit, the magnitude of magnetizing current, I_m is calculated as

$$I_m=\left[\left(i_{sq}+i_{rd}\right)^2+\left(i_{sq}+i_{rq}\right)^2\right]^{\frac{1}{2}} \quad (8)$$

Capacitor side equations are

$$p\,[V_{sG}]=(1/C)[i_c] \quad (9)$$

Also further,

$$[i_C]=[i_{sG}]+[i_L] \quad (10)$$

Where, $[V_{sG}]=[i_{sG}]+[i_L]$ column matrices represent the direct and quadrature axis components of the capacitor current generator stator current and load current respectively, . Load side equation is given as

$$[V_{sG}]=L_{Lp}[i_L]+R_L[i_L] \quad (11)$$

Thus, it is seen that the equations from (1) to (11) are a complete transient model of the SEIG in the d-q quasi stationary reference frame.

V. Calculation of Output Power

The mechanical torque equation of the machine is:

$$T_{em}-T_L=J\frac{d\omega_m}{dt} \quad (12)$$

Where, T_{em} is the electromagnetic torque created by the wind turbine on the rotor, T_L is the load torque on the rotor shaft , J is the inertia of the rotor and ω_m is the mechanical speed is given by the equation (13):

$$\omega_m=\frac{1}{p}\frac{d\theta}{dt} \quad (13)$$

Where, θ is the angular position of the rotor and p denotes the number of machine pole pairs.

The electromagnetic torque is given by the following equation (14):

$$T_{em}=p\,I_s^t\left\{\frac{d}{d\theta}[L_m]\right\}I_r \quad (14)$$

Where, I_s^t the field current and I_r is the armature current. Generator power output is given by the equation (15):

$$P_{out}=T_{em}\omega_m \quad (15)$$

$$P_{out}=\omega_m\left[p\,I_s^t\left\{\frac{d}{d\theta}[L_m]\right\}I_r\right] \quad (16)$$

$$P_{out}=I_s^t.\,I_r\left[\frac{d}{dt}\left(\frac{N\phi_r}{I_s}\right)\right] \quad (17)$$

$$P_{out}=N.\,e.\,I_r \quad (18)$$

Where, N is the number of armature windings, e is the emf induced in the generator. The Total power output is given by

$$P_{out}=N.\,P_r \quad (19)$$

Where, P_r is the generator power output.

The generator power output is directly proportional the wind velocity and inversely proportional to mutual inductance of the windings and vice versa.

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VI. MATLAB/SIMULINK Model of SEIMWPG

The MATLAB/SIMULINK is a powerful software tool for modeling and simulation of the proposed system. The equations from (1) to (11) have been implemented in the MATLAB/SIMULINK environment using various blocks as in Fig.3 (a) MATLAB/SIMULINK model for wind power generation System. Fig.3 (b) shows the Sub- system of SEIMWPG system, which contains the various outputs of the system.

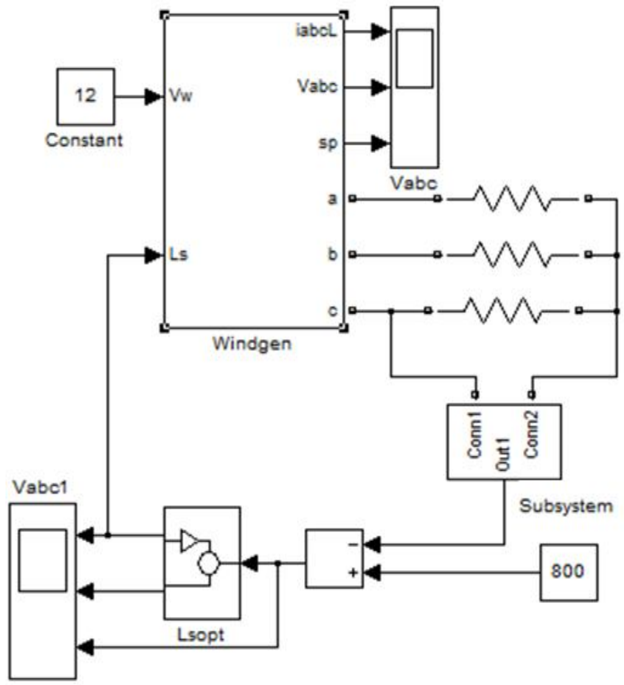

Figure 3(a). MATLAB/SIMULINK model for wind power generation System

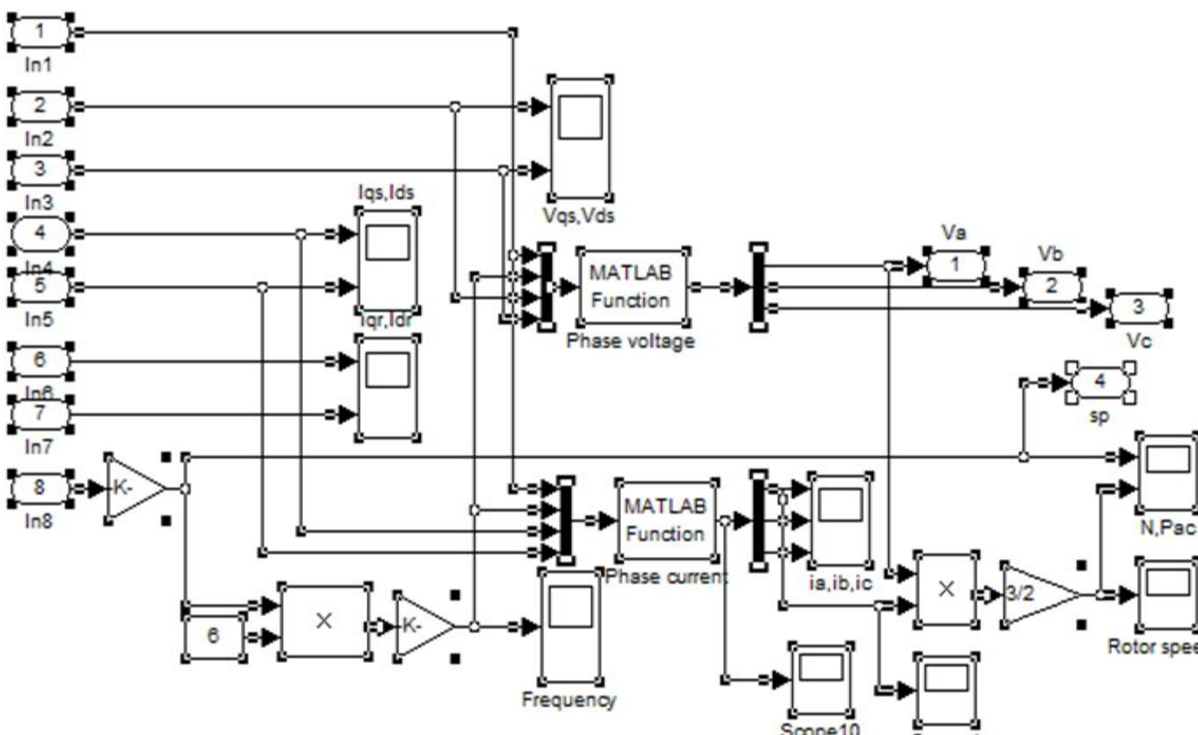

Figure 3(b). Sub- system model of SEIMWPG output

VII. Simulation Results and Discussions

The SEIMWPG machine model has been simulated using MATLAB/SIMULINK tool and the various results have plotted as below in Fig. 4(a) to 4(e).

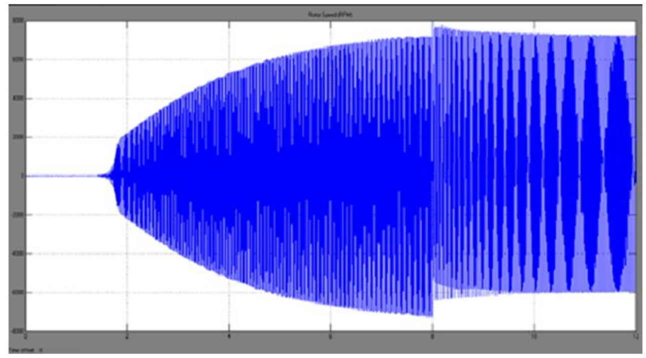

Figure 4 (a). Rotor Speed (rpm), with respect to wind velocity (m/s)

Fig. 4(a) shows the wind speed is fluctuated and the rotor speed of the generator also been variable in its magnitude.

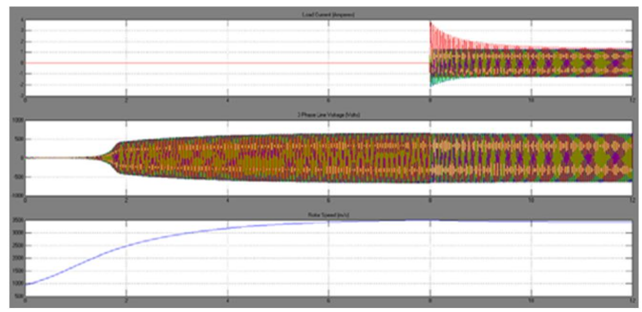

Figure 4(b). Wind velocity (m/s), 3 phase line voltage (volts), and Load current (Amperes)

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In Fig. 4(b), it is shown that the wind speed, voltage generated and loads current. The voltage generated is maintained at rated value, irrespective of the wind speed variations, with the mutual inductance of machine windings. The load current increases with respect to the increasing of load connected.

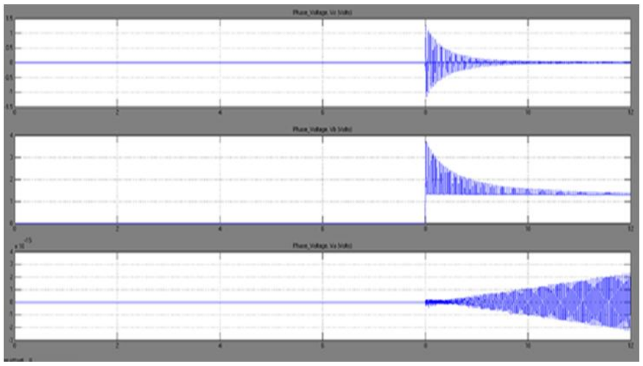

Figure 4(c). The generator phase voltages: V_a, V_b, and V_c in volts.

Fig. 4(c), shown that the generator phase voltages V_a, V_b, and V_c, phase voltages displaced by 120 electrical degrees according to the three phase windings.

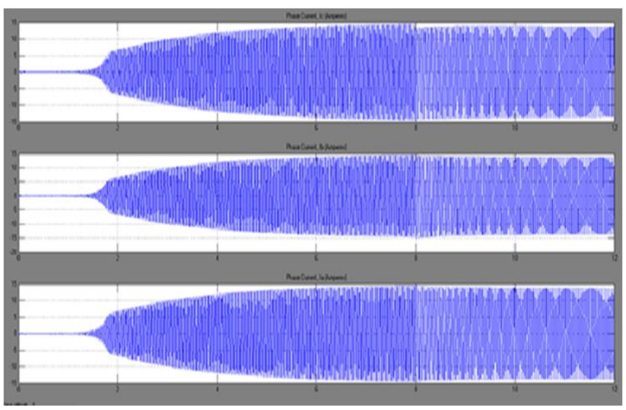

Figure 4(d). Phase currents: I_a, I_b, and I_c in Amperes

Fig. 4(d), shown that the generator phase currents I_a, I_b, and I_c, these are the phase currents displaced by 120 electrical degrees according to the three phase windings.

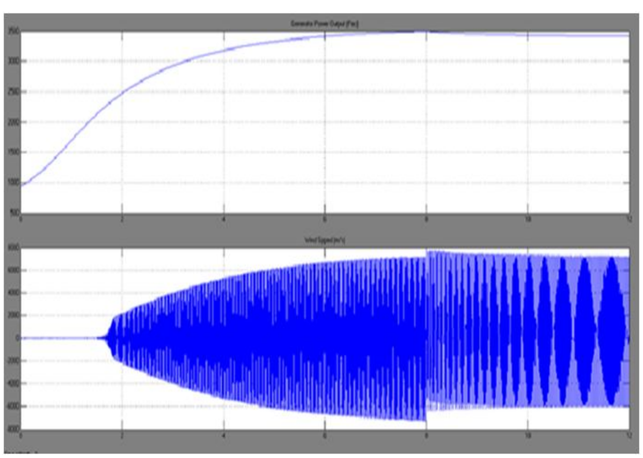

Figure 4(e). Wind velocity (m/s) and Generator output Power, P_{ac}, (kW).

In Fig. 4(e), it shown that the wind speed and the generator power output is met rated value by the variation of the mutual inductance of the generator windings, irrespective of the various wind velocities.

VIII. Conclusion

This paper presented a modeling and simulation of self-excited induction machine for wind power generation. The test model is designed and tested for various wind velocities and voltages. This model will be the best suit for power generation from the renewable energy source i.e., winds energy. The variation of the mutual inductance of stator and rotor windings has been taken care of the generator speed fluctuations due to the wind speeds. The windings mutual inductance of the machine can be varied in accordance with the wind speed fluctuations, and to maintain the output voltage generation at rated value. It is shown that the simulated results for various wind speeds in this system should be useful to solve the power shortage and it will be enhanced to design for large scale generation and to meeting the future power demands all over the world.

Appendix

Table I. Machine Parameters

Sl. No.	Details of Machine		
	Parameters	**Ratings**	**Units**
1	Stator resistance, R_s	1.0	Ohms
2	Rotor resistance, R_r	0.77	Ohms
3	Stator Leakage Inductance, X_{ls}	1.0	Ohms
4	Rotor Leakage Inductance, X_{lr}	1.0	Ohms
5	Current density, J	0.1384	K_g-m^2

Table II. Machine Specifications

Sl. No.	Details of Machine		
	Specifications	Ratings	*Units*
1	Power rating	10h.p (7.5kW)	*Kilo-watts*
1	Number of phases	3, Delta Connection	-
2	Number of poles	4	-
3	Voltage rating	415	*Volts*
4	Current rating	3.8	*Amperes*
5	Base Current/rated Current	2.2	*Amperes*
6	Frequency	50	*Hertz*

Table I, and Table II, are shown that, the machine parameters and machine specifications are respectively for system design process.

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Biographies

R. Janakiraman received AMIE in Electrical Engineering from The Institution of Engineering (India) 1999, M.E. degree in Power Systems Engineering from College of Engineering, Guindy, Anna University, Chennai, India, in 2005.

Currently, he is with the position of Assistant Professor in the Department of Electrical and Electronics Engineering, of Sri Ramanujar Engineering College, Anna University Chennai, Tamil Nadu, India, pursuing Ph.D. in Jawaharlal Nehru Technological University, India. He is a life member of IEI. His research interests include renewable energy, power electronics, power systems and embedded systems.

S. Paramasivam received the B.E. degree from GCT, Coimbatore, in 1995, the M.E. degree from P.S.G. College of Technology, Coimbatore, in 1999, and the Ph.D. degree from College of Engineering, Anna University, Chennai, in 2004.

His interests include power electronics, AC motor drives, DSP-and FPGA-based motor controls, power-factor correction, magnetic design, fuzzy logic, neural networks, and controller design for wind energy conversion systems. He has published over 72 papers on various aspects of SRM and induction motor drives in international journals and conferences worldwide.

Presently he is working at ESAB Group, Chennai, as the R&D Head for equipments and cutting systems. He is the Editor-in-Chief of the International Journal of Power Electronics, and an Editorial Board Member of the International Journal of Adaptive and Innovative Systems and International Journal of Renewable Energy Technology. He is also a Reviewer for many IEEE journals, Acta Press, Inderscience journals, Elsevier journals, Hindwai journals, and IEEE conferences.

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